



Incorporation of Condensation Heat Transfer in a Flow Network Code

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In this paper we have investigated the condensation of water vapor in a short tube. A numerical model of condensation heat transfer was incorporated in a flow network code. The flow network code that we have used in this paper is Generalized Fluid System Simulation Program (GFSSP). GFSSP is a finite volume based flow network code. Four different condensation models were presented in the paper. Soliman's correlation has been found to be the most stable in low flow rates which is of particular interest in this application. Another highlight of this investigation is conjugate or coupled heat transfer between solid or fluid. This work was done in support of NASA's International Space Station program.



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Here are the topics of presentation. In the Introduction, the background and objective of the paper will be explained. Then the problem considered will be described. A brief description of the general purpose flow network code will be followed. Numerical models of condensation heat transfer and solid to fluid heat transfer will be described. The paper will conclude with the discussion of numerical results, conclusions, References and Acknowledgements.

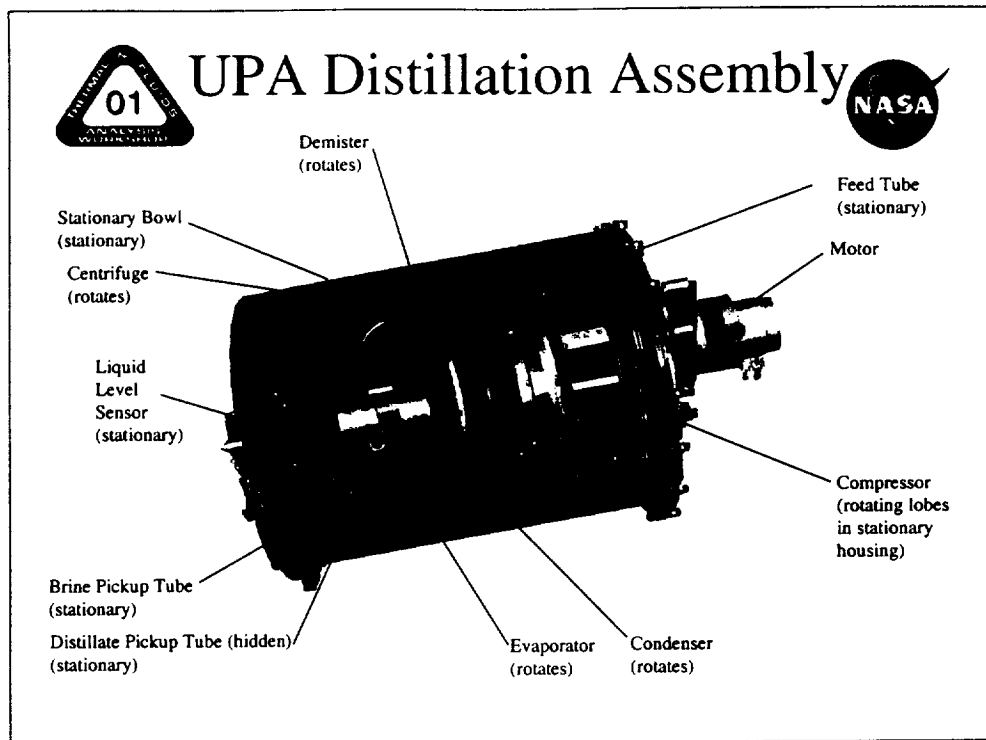


Introduction

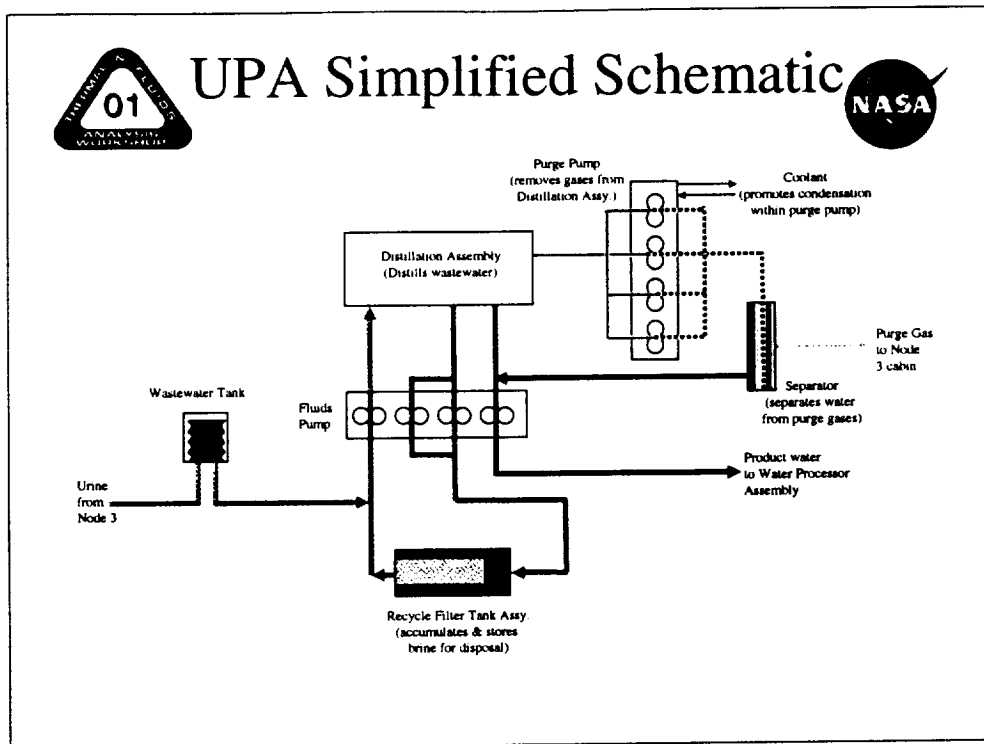


- Pure water is distilled from waste water in International Space Station
- Distillation assembly consists of evaporator, compressor and condenser
- Vapor is periodically purged from the condenser to avoid vapor accumulation
- Purged vapor is condensed in a tube by coolant water prior to entering purge pump
- The paper presents a condensation model of purged vapor in a tube

This work has been done in support of design and testing of Urine Processing Assembly (UPA) which is a part of Environmental Control and Life Support System (ECLSS) of International Space Station (ISS). Pure water is reclaimed from waste water through a distillation process. The distillation assembly consisting of evaporator, compressor and condenser employs a regenerative process to reduce power consumption. Evaporator receives the heat from the condenser for converting liquid to vapor. Condenser rejects that heat in the process of condensation. The condenser does not condense all the vapor it receives. Therefore, vapor is periodically purged from the condenser to avoid vapor accumulation. Purged vapor is condensed in a tube by coolant water prior to entering the purge pump. The purpose of the paper is to present a numerical model of condensation of purged vapor in a tube.



Distillation assembly is shown in this slide. The feed tube supplies the waste water towards one end of the assembly. The inner and outer surface of the centrifuge are evaporator and condenser respectively. The rotating surface makes a small angle with the axis of rotation. The component of centrifugal force along the surface of the rotating drum drives the flow from one end to the other. While traveling from right to left, the waste water receives the necessary heat from the condenser to evaporate. The compressor compresses the vapor to a higher pressure. The superheated vapor enters the compressor, cools down to saturation temperature and condenses.



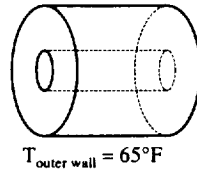
This slide shows the schematic of waste and product water distribution. Waste water is supplied to the evaporator of the Distillation Assembly (DA) through fluid pump. Only a fraction of the water is evaporated. The remaining water is recycled back to the DA through recycle filter tank. The purge pump draws mixture of non-condensable gas and vapor from the condenser. The vapor is condensed by the circulating coolant water to improve the performance of the pump. The product water shown in blue is collected from the condenser of distillation assembly and gas and liquid separator.



Problem Description



Superheated
Water Vapor
 $P_{\text{inlet}} = 0.95 \text{ psia}$
 $T_{\text{inlet}} = 101^\circ\text{F}$



Saturated
Water Vapor
 $P_{\text{outlet}} = 0.5 \text{ psia}$

Inner Tube Diameter = 0.125 inch
Outer Tube Diameter = 1 inch
Length = 4 inches
Material is Titanium

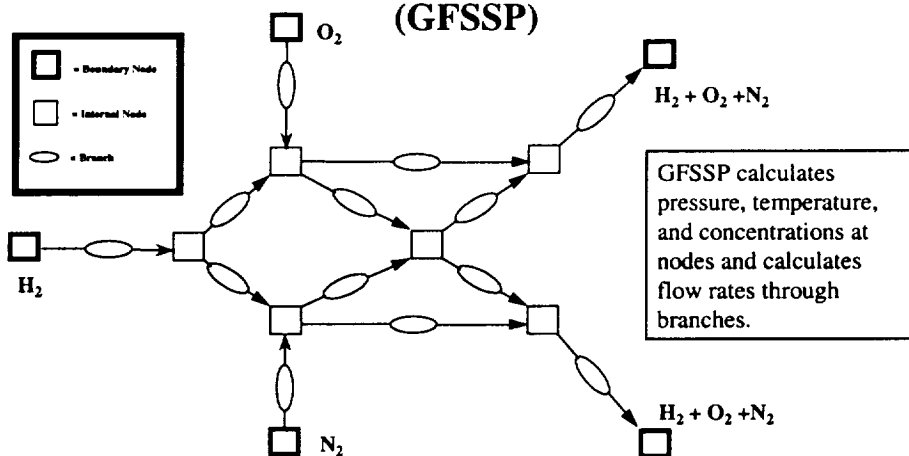
Calculate the Quality and Heat Transfer Properties
of the Water as it Condenses in the Pipe

Model consists of 2 Boundary Nodes and 28 Internal Nodes
and Models Conduction through the Tube Wall

This paper considers the flow of superheated vapor through a 4-inch long Titanium tube with inside and outside diameter of 0.125 inch and 1 inch respectively. The outside tube is cooled by coolant water at 65°F . The problem is to calculate the quality and heat transfer properties of the water as it condenses in the tube. A network flow analysis code, GFSSP will be used to model the flow. The numerical model has two boundary nodes at inlet and outlet where the pressures and temperatures are specified. There are 28 internal nodes where pressures, temperatures and quality will be calculated. There are 29 branches where flowrates are calculated.



Generalized Fluid System Simulation Program (GFSSP)



GFSSP flow circuit consists of boundary nodes, internal nodes and branches. At boundary nodes, pressures, temperatures, concentrations are supplied. The code calculates pressures, temperatures and concentrations at interior nodes and flowrates in branches.



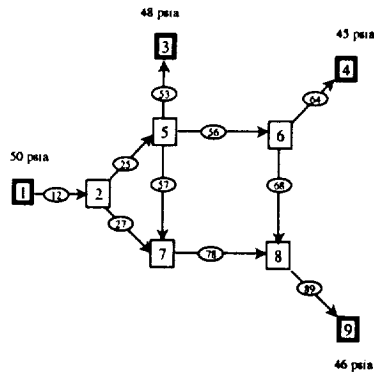
GFSSP Finite Volume Method

- Finite Volume Method is based on conservation principle of Thermo-Fluid Dynamics
- In Classical Thermodynamics we analyze a single control volume
- In Finite Volume Method, flow domain is discretized into multiple control volumes and a simultaneous analysis is performed
- Finite Volume Method can be classified into two categories:
 - Navier-Stokes Solution (Commonly known as CFD)
 - Network Flow Solution (NFS)

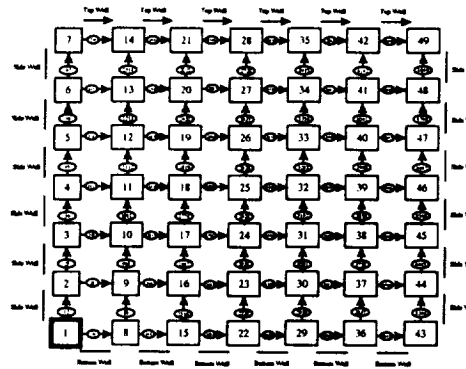
GFSSP uses finite volume formulation to represent mass, momentum, energy and specie conservation in a generalized flow network. Finite volume method is an extension of control volume method from classical thermodynamics. In finite volume method flow domain is discretized into multiple control volumes and in each control volume conservation equations for mass momentum, energy and specie are written. Solution of these equations give pressure, flowrate, temperature and concentration fields. Navier-Stokes solutions are typically performed in structured co-ordinate system. However, an unstructured co-ordinate system must be developed for a generalized network flow solution. GFSSP uses an unstructured co-ordinate system.



GFSSP Finite Volume Method

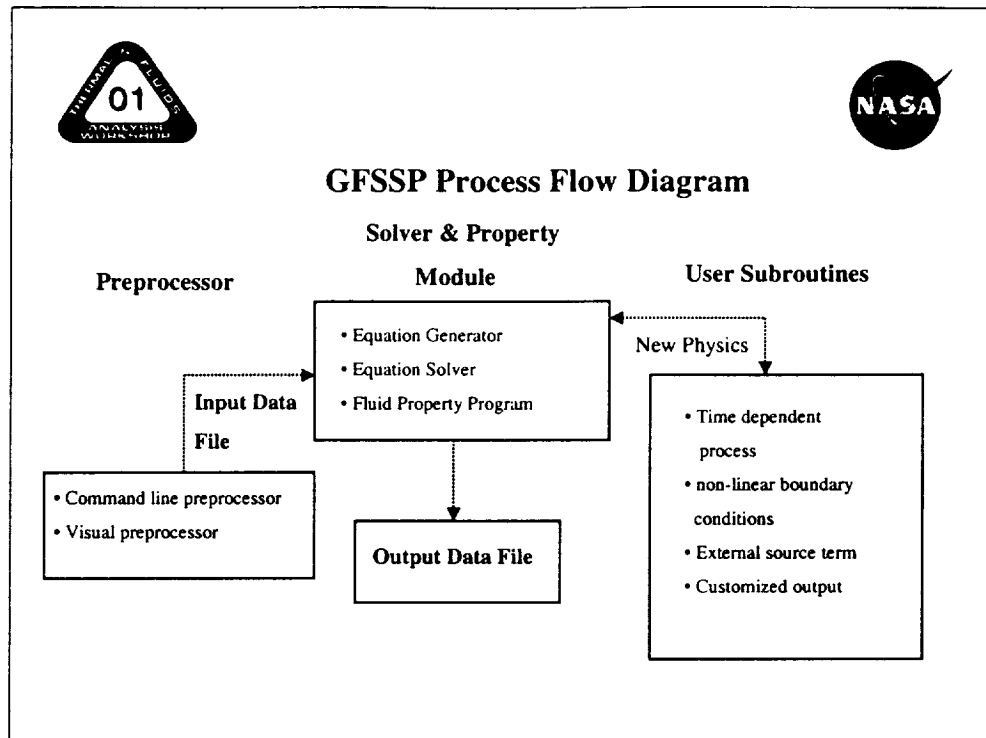


Network Flow Solution (NFS)



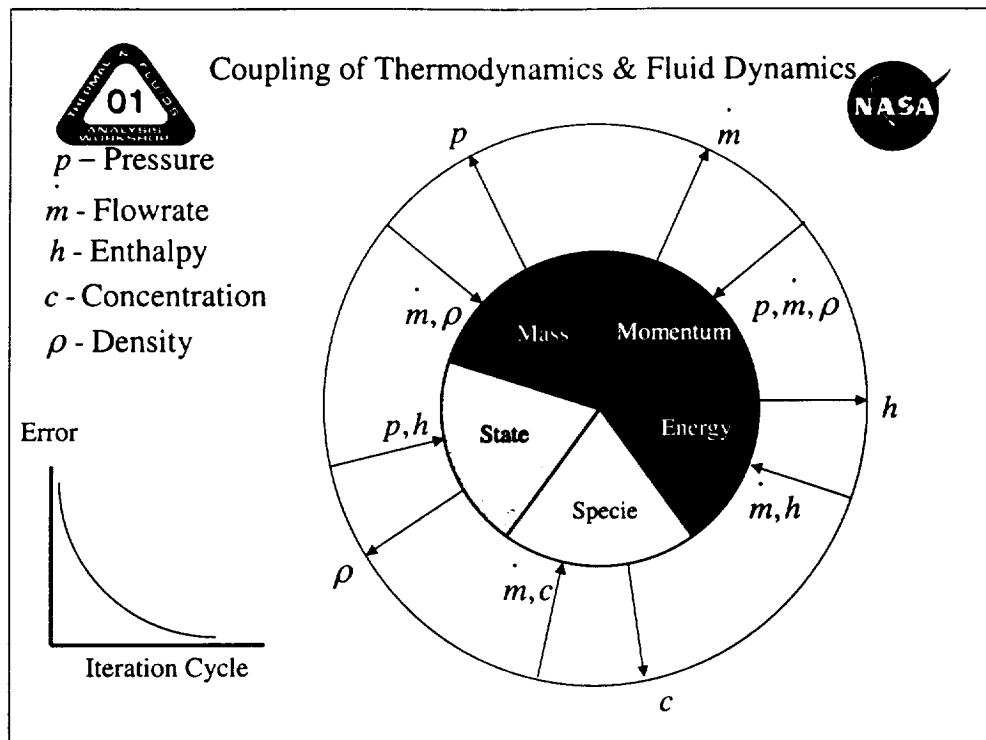
Navier-Stokes Solution (CFD)

In the Network Flow Solution, an one-dimensional momentum equation is solved in branches. In Navier-Stokes Solution, a multi-dimensional form of momentum equation is solved. Longitudinal momentum is transported by transverse component of velocity.



This chart shows GFSSP's process flow diagram. It also shows the programming language and operating system. The code has three major modules: Preprocessor, Solver & Property Module and User Subroutines. The user creates the input data file with the help of Visual preprocessor. You will see how it works in the video demonstration. The Solver & Property Module reads the input data file and generates and solves the equations with the help of fluid property programs. During solution, it receives input from User Subroutines, if needed. Finally it generates the output data file. User Subroutine is a module where user can add new capabilities and options in the code. A few examples of such capabilities are listed in this box: Time dependent process, non-linear boundary conditions, external sources and customized out are just a few examples of capabilities user may like to add. Any specific capability can be added in the User Subroutine. As mentioned earlier that there was no need to develop any specific purpose code. All you need to do is to develop your own subroutine and integrate with GFSSP's solver module.

The preprocessor is written in C++ . Solver Module and User Subroutine are written in FORTRAN. The identical source code runs in PC/Unix and Macintosh.



The coupling of Thermodynamics and Fluid Dynamics is shown in this chart. GFSSP solves for fluid mass, momentum, energy and specie conservation equations in conjunction with the thermodynamic equation of state. Pressure, mass flowrate, enthalpy, concentration and density are calculated by solving these equations by an iterative method. The unique aspect of GFSSP is to include the equation of state of real fluid in the formulation. The intent of the numerical scheme is to reduce the conservation error with iteration.

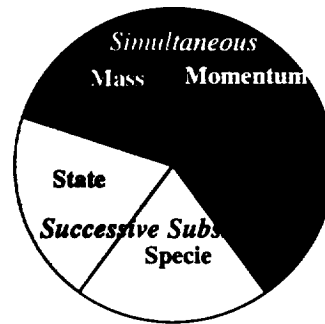


GFSSP Solution Scheme

SASS : Simultaneous Adjustment
with Successive Substitution

Approach : Solve simultaneously
when equations are strongly
coupled and non-linear

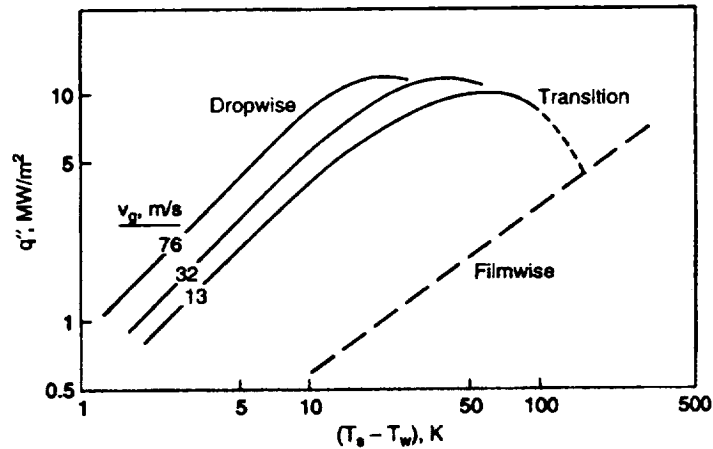
Advantage : Superior
convergence characteristics with
affordable computer memory



GFSSP has an Unique Solution Scheme called SASS (Simultaneous Adjustment with Successive Substitution). There are two numerical schemes for solving non-linear algebraic equations: Simultaneous and Successive Substitution. In SAAS, strongly coupled equations are solved simultaneously and the equations that are weakly coupled are solved by the successive substitution scheme. In GFSSP mass and momentum equations are more strongly coupled and therefore they are solved simultaneously. The state, energy and specie equations are solved by the successive substitution method. We get superior convergence characteristics with affordable memory.



Condensation Heat Transfer



In the last twenty years, it has been demonstrated that, just as with boiling heat transfer, a characteristic condensation curve exists that includes a dropwise region, a filmwise region, and a transition region. This slide shows some representative condensation curve for steam at atmospheric pressure. At a fixed vapor velocity, at very low surface subcoolings, dropwise condensation occurs. However, at large enough subcooling, relatively thick continuous liquid film tries to occur. A transition region follows where the heat flux decreases and approaches the filmwise condensation curve.

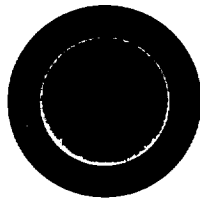


Heat transfer correlations

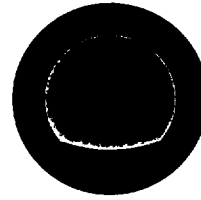


Akers, et al, 1959 – Annular Correlation
Boyko and Kruzhulin, 1967 – Annular Correlation
Chato, 1962 – Stratified Correlation
Soliman, et al, 1968 – Generalized Correlation

Chose Soliman correlation for its stability and generality



Annular Condensation



Stratified Condensation

The two condensation regimes studied were annular and stratified condensation. Annular condensation occurs when the liquid surface on the inside of a tube forms evenly, while in stratified condensation, gravity causes the liquid to pool towards one side of the tube. Four correlations were chosen for this study. The Akers correlation and the Boyko and Kruzhulin correlation calculate heat transfer coefficients for annular condensation. The Chato correlation calculates for stratified condensation, and the Soliman correlation can calculate coefficients for both annular and stratified condensation. The Soliman correlation was most promising because it was more general, and also because it was the most stable in GFSSP at the lower flowrates needed for the Space Station application.

Each correlation was inputted into the user subroutine URCOND.FOR, which is a subroutine in GFSSP that allows users to input custom correlations for heat transfer.



Soliman Correlation for Heat Transfer Coefficient for Annular Flow Condensation



$$h = 0.036 \text{Pr}^{0.43} F_0^{0.5} \left[\frac{k_f \rho_f^{0.5}}{\mu_f} \right]$$

$$F_0 = F_f + F_m \pm F_a$$

$$F_f = 0.045 \text{Re}_f^{-0.2} \left[\frac{\pi^2 \rho_c D^4}{8 W_f^2} \right] \left[x^{1.8} + 5.70 \left(\frac{\mu_c}{\mu_f} \right)^{0.0223} (1-x)^{0.470} x^{1.33} \left(\frac{\rho_c}{\rho_f} \right)^{0.204} + 8.1 \left(\frac{\mu_c}{\mu_f} \right)^{0.105} (1-x)^{0.940} x^{0.660} \left(\frac{\rho_c}{\rho_f} \right)^{0.122} \right]$$

$$F_m = 0.5 \left(D \frac{dx}{dz} \right) \left[\frac{\pi^2 \rho_c D^4}{8 W_f^2} \right] \left[2(1-x) \left(\frac{\rho_c}{\rho_f} \right)^{1/3} + \left(\frac{1}{x} - 3 + 2x \right) \left(\frac{\rho_c}{\rho_f} \right)^{4/3} + (2x - 1 + \beta x) \left(\frac{\rho_c}{\rho_f} \right)^{1/3} + \left(2\beta - \frac{\beta}{x} - \beta x \right) \left(\frac{\rho_c}{\rho_f} \right)^{2/3} + 2(1-x-\beta+\beta x) \left(\frac{\rho_c}{\rho_f} \right) \right]$$

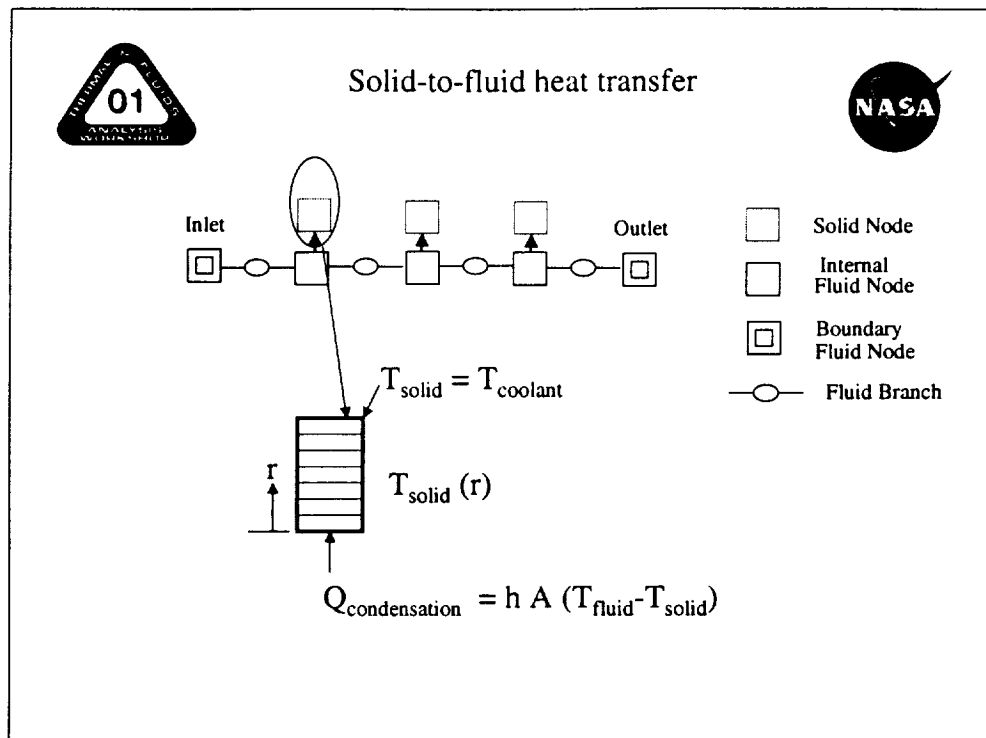
$$F_a = 0$$

F_f : Effect of two-phase friction

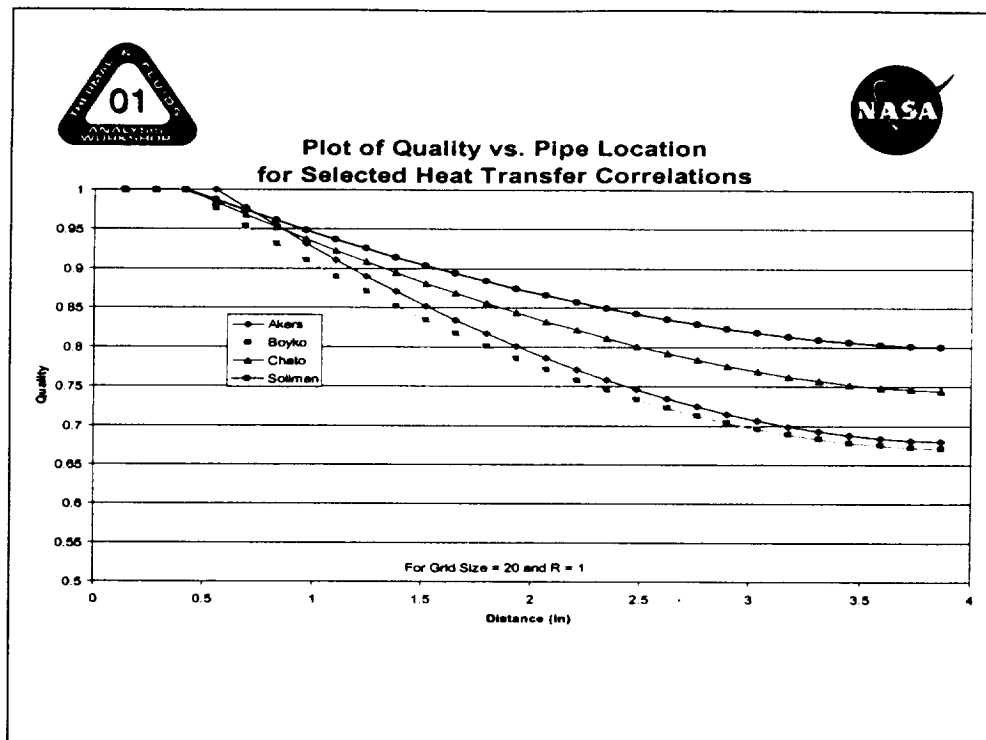
F_m : Effect of momentum changes in the flow

F_a : Effect of axial gravitational field on the wall shear stress

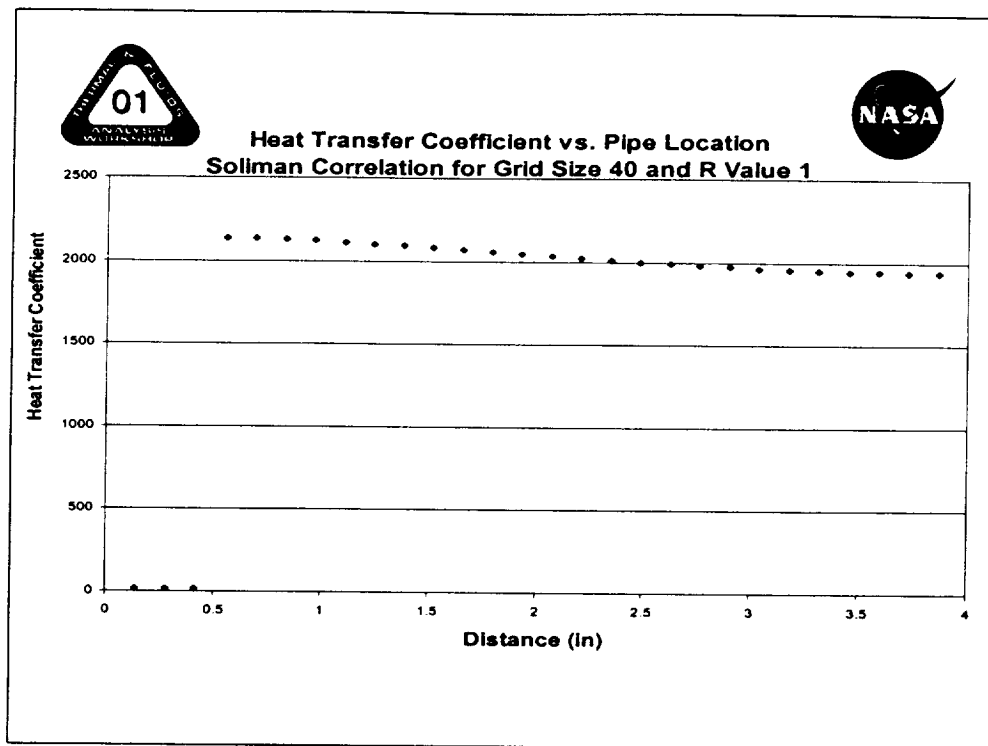
Soliman et al. studied the interaction between friction, momentum, and gravity, as they affect the heat transfer process during annular flow condensation inside tubes. Analytical forms for each of these forces are derived and incorporated in a correlation that predicts the heat transfer coefficient. The predictions agree well with the available experimental data over a wide range of vapor velocities and over a range of Prandtl number from 1 to 10. Setting the F_a term to zero in this calculation allows the Soliman correlation to predict annular condensation heat transfer coefficients.



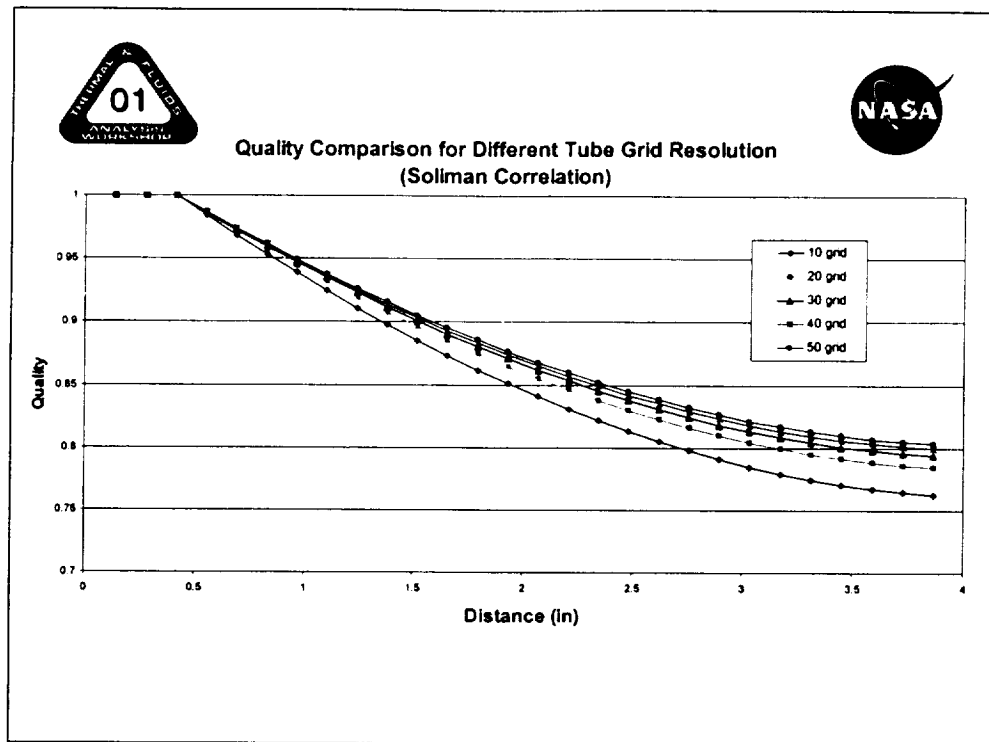
In the numerical model each fluid node is connected to a solid node to allow heat transfer between solid and fluid. The solid wall was discretized into 40 to 50 control volumes in the radial direction. The number of control volumes can be adjusted. The temperature of the outer wall is set to the coolant temperature and a heat flux condition was set at the inner wall. Heat conduction equation was solved in each control volume to calculate the radial temperature distribution.



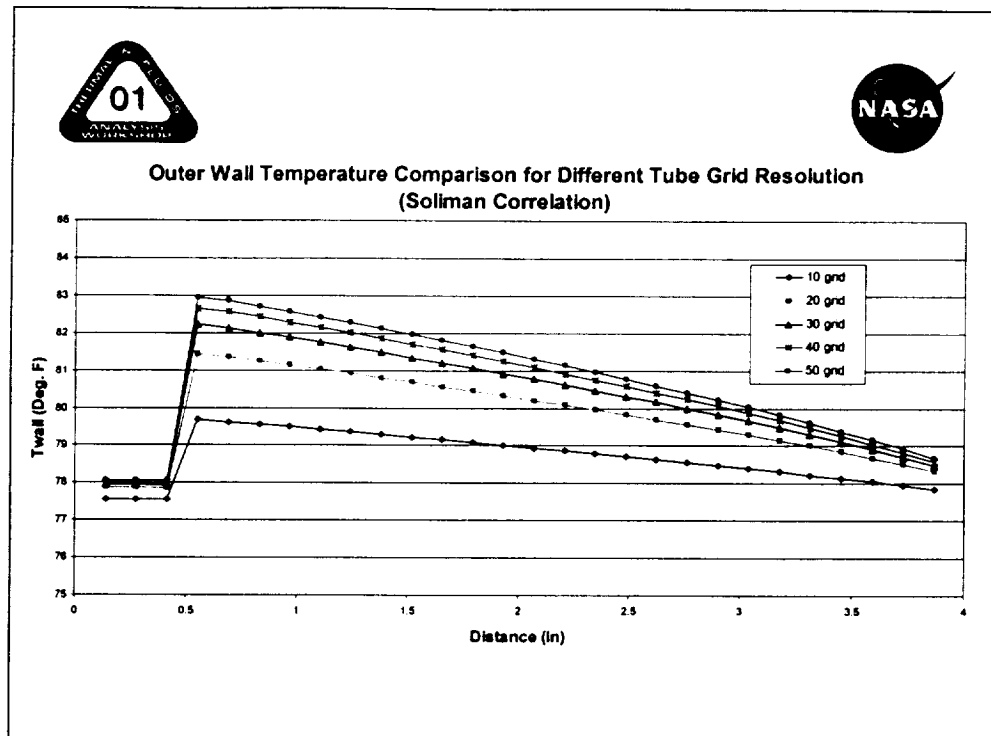
This plot shows the distribution of quality along the axis of the tube. Four models were compared. For each model condensation begins after 0.5 inch from the inlet. Soliman correlation predicts the highest quality at the tube exit and the most conservative from design view point.



This plot shows the distribution of heat transfer coefficient along the axis of the tube. The instant rise in heat transfer coefficient can be noted with the onset of condensation after 0.5 inch from inlet.



The grid size determines how many control volumes the tube is cut into. The higher the grid number, the smaller the individual tube volumes. A higher number means a higher resolution mesh. The quality at five grid resolutions was calculated and the results plotted. The results show that at higher mesh resolutions, the calculations become closer, indicating that we were approaching the point of diminishing returns – a higher resolution will not yield results much more accurate. At higher resolutions, the changes between tube layers becomes so small that computation errors result.



This graph shows a comparison of outer wall temperature as a function of the grid resolution. Again, at higher resolutions, the results get closer together, indicating that results do not change much after the tube is divided into about 40 or so parts.



Conclusions



- A condensation heat transfer model was successfully incorporated in a general purpose flow network code
- The numerical model considers solid-to-fluid heat transfer
- Soliman et al's correlation of condensation heat transfer is recommended due to its generality and stability



References & Acknowledgements

References:

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1. Rohsenow, W. M., Hartnett, J. P. and Cho, Y. I., "Handbook of Heat Transfer" 3rd Edition, McGraw Hill, 1998
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Acknowledgement:

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